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Key Points:
- Dry Valley soils generate dust comparable to sources in the Southern Hemisphere
- The soluble iron content is larger than other dust sources in the region
- In the future the increased delivery of iron to the Southern Ocean is likely

Correspondence to:
L. Wang,
lxwang@iupui.edu

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Antarctica's Dry Valleys: A potential source of soluble iron to the Southern Ocean?

Abinash Bhattachan[1], Lixin Wang[2], Molly F. Miller[3], Kathy J. Licht[2], and Paolo D'Odorico[1,4]

[1]Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia, USA, [2]Department of Earth Sciences, Indiana University-Purdue University at Indianapolis, Indianapolis, Indiana, USA, [3]Department of Earth and Environmental Sciences, Vanderbilt University, Nashville, Tennessee, USA, [4]SESYNC, University of Maryland, Annapolis, Maryland, USA

Abstract The soluble iron content and dust emission potential of sediment samples collected from the Taylor Valley in the McMurdo Dry Valleys (MDVs) and sea ice in the McMurdo Sound were evaluated to determine whether inputs to the Southern Ocean may be sufficient to affect ocean productivity. Our results show that the dust-generating potential from the MDVs soils are comparable to those of sediments from other major dust sources in the Southern Hemisphere. Sediments from the MDVs and sea ice are one order of magnitude richer in soluble iron than those in other dust sources in the Southern Hemisphere. Forward trajectory analyses show that the dust from the MDVs is likely to be deposited in the Southern Ocean. These results provide evidence of the possible supply of soluble iron to the Southern Ocean associated with dust transport from the MDVs, should climate change expand the exposed areas of the continent.

1. Introduction

Most dust emissions on Earth occur in the Northern Hemisphere, whereas in the Southern Hemisphere the dust sources are fewer and not as prolific [*Goudie and Middleton*, 2006]. The lower atmospheric dust concentrations in the Southern Hemisphere limit the supply of important micronutrients (e.g., iron) to the Southern Ocean, thereby constraining its productivity [e.g., *Martin*, 1990; *Jickells et al.*, 2005; *Okin et al.*, 2011]. This fact explains why the Southern Ocean exhibits high nutrient low chlorophyll (HNLC) regions. Iron enrichment studies confirm that the productivity of HNLC waters of the Southern Ocean is indeed limited by iron [*Boyd et al.*, 2000]. Sources of iron to the Southern Ocean include dust [*Jickells et al.*, 2005; *Cassar et al.*, 2007], upwelling [*Tagliabue et al.*, 2010], and subglacial meltwater [*Death et al.*, 2014]. Increased delivery of iron-rich dust during glacial maxima has been invoked to explain periods of enhanced Southern Ocean productivity and the consequent fluctuations in atmospheric CO_2 concentrations during glacial-interglacial transitions [*Martin*, 1990; *Harrison et al.*, 2001]. Because the current deposition flux of soluble iron in dust to the Southern Ocean is low [e.g., *Okin et al.*, 2011], an emergence of new dust sources in the Southern Hemisphere can affect ocean biogeochemical cycles and this could have large-scale implications to carbon cycling. Presently, the supply of soluble iron through the mineral dust in sea ice accounts for only 5% of the total productivity of the Southern Ocean [e.g., *Edwards and Sedwick*, 2001], but enhanced dust emissions from Antarctica could have an important impact on the productivity of downwind HNLC ocean regions. To this end, in this study we investigate the extent to which dust from the sediments of the McMurdo Dry Valleys (MDVs) of Antarctica could increase in the future and contribute to the supply of micronutrients (in the form of soluble iron) to the Southern Ocean.

The MDVs are the largest (~4800 km^2) ice-free area on Antarctica [*Doran et al.*, 2002]. The abundance of source material (mostly derived from moraines deposited by an ice sheet that entered the MDVs during the Last Glacial Maximum) coupled with wind speeds that exceed the threshold for entrainment makes this region the dustiest in Antarctica [*Chewings et al.*, 2014]. Climate change studies indicate that temperatures over Antarctica are expected to increase in the coming decades [*Shindell and Schmidt*, 2004; *Bromwich et al.*, 2013]. Some areas of West Antarctica have shown measurable ice mass loss and thinning, especially in coastal regions [*Rignot et al.*, 2008; *Joughin and Alley*, 2011; *Mouginot et al.*, 2014]. It is estimated that between 1957 and 2006, the air temperature in Antarctica has increased on average by 0.12°C per decade, with West Antarctica warming at a slightly higher rate (0.17°C per decade) [*Steig et al.*, 2009; *Bromwich et al.*, 2013].

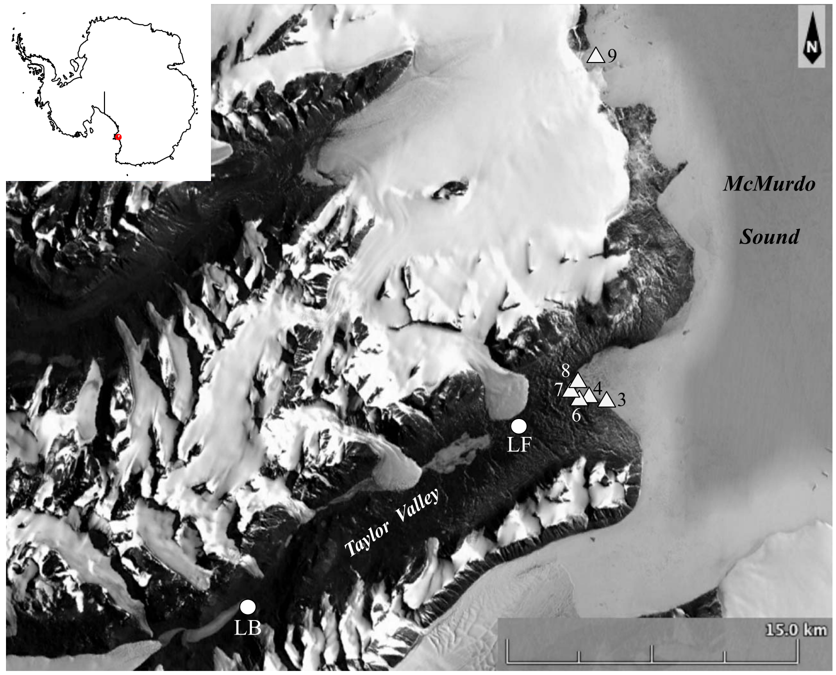

Figure 1. Study sites in the Taylor Valley, McMurdo Dry Valleys (LB: Lake Bonney; LF: Lake Fryxell). The sea floor sediments were sampled in cores taken at Explorers Cove, 20 m beneath the surface (#9). Two samples (#8) are windblown sediment collected on the top of the sea ice. Samples from other locations (3, 4, 6, and 7) are from the uppermost 4 cm of short cores of the seafloor (20 m deep from the surface) underneath the multiyear sea ice.

While a number of authors have identified the sources of the dust reaching Antarctica [e.g., *Basile et al.*, 1997; *Revel-Rolland et al.*, 2006; *Gassó et al.*, 2010], fewer studies have investigated the modern dust flux from Antarctica. *Malin* [1991] provided the first estimate of long-term aeolian sediment flux, while *Lancaster* [2002] later measured dust fluxes within the MDVs. *Atkins and Dunbar* [2009] stressed how the potential amount of dust from Antarctica could fertilize the Southern Ocean, though more recently the significance of these dust fluxes has been challenged [*Chewings et al.*, 2014]. The soluble iron content in the dust from the MDVs, however, remains poorly quantified, and it is unclear whether dust emissions from the exposed surfaces in the MDVs can reach the HNLC waters of the Southern Ocean. To this end, we use a laboratory dust generator to assess the potential of the exposed sediments to be dust sources and compare it to other currently active dust sources in the Southern Hemisphere. We also estimate the soluble iron content in aeolian sediments from the MDVs and sediment under the sea ice and use trajectory analyses to determine the footprint of the deposition of dust from the MDV.

2. Methods

2.1. Study Sites

Soil samples from the MDVs were collected in the Taylor Valley (77°37′S, 163°00′E) in the dry edges of Lake Fryxell and Lake Bonney (Figure 1). Three replicates from each of these sites were sampled in 2008 from the top 10 cm of the exposed soil surface. Lake regions within the MDVs are ideal for sampling because there is a large grain size range in a relatively small area and fine particles are prone to aeolian erosion and entrainment in the airflow. A subsample of soil from the Taylor Valley was run through a particle size analyzer (LS 13 320, Beckmann-Coulter) to calculate grain size distribution. Seafloor sediment samples from Explorers Cove at the mouth of the Taylor Valley were from cores taken by divers beneath the multiyear sea ice (Figure 1 and Table 1). Two samples from the surface of the sea ice were also sampled, as was a seafloor core sample from ~16 km north of Explorers Cove (Figure 1 and Table 1).

2.2. Dust Generator Experiment

Samples of sediment susceptible to aeolian transport (i.e., only sediments from the Taylor Valley sites) were analyzed for dust emitting potential using a laboratory dust generator (Custom Products, Big Spring, TX). For each

Table 1. Soluble Iron Content (mg/g) of Sediments From the Taylor Valley, the Shallow Sea Floor, and Sea Ice (Figure 1, From Lakes Bonney ($n=3$) and Fryxell ($n=3$) the Seafloor Underneath Multiyear Sea Ice (3 ($n=3$), 4 ($n=5$), 6 ($n=3$), 7 ($n=3$), and 9 ($n=5$)) and the Sea Ice Surface (8 (Two Samples Without Replicates)))[a]

Site (Figure 1)	Fe(II) (mg/g)	Clay (%)	Silt (%)
Lake Bonney (LB)	1.36 ± 0.07	1.04 ± 0.07	2.28 ± 0.70
Lake Fryxell (LB)	1.51 ± 0.18	1.60 ± 0.48	3.57 ± 1.13
9	1.55 ± 0.01		
3	1.55 ± 0.005		
7	1.56 ± 0.01		
4	1.55 ± 0.01		
6	1.53 ± 0.03		
8	1.55		
8	1.56		

[a]The grain size distribution was calculated for a subsample of the soil collected from Lakes Bonney and Fryxell.

run, 1 g of air-dried sediment was used for each sample and placed in a sealed tube that rotates about a horizontal axis at the speed of 13 rpm. An air pump draws air from the tube to a settling chamber at a rate of 0.014 $m^3 s^{-1}$. Thus, the dust produced by the impact of the sediment with the bottom of the rotating tube (and the consequent breakup of aggregates) is transported to the settling chamber, where dust concentrations are measured using an aerosol spectrometer (Grimm, Model 1.108) which provides real time readings (a reading each 6 s) of particle counts per volume for different size classes (0.3 and 20 μm in diameter). In this study we focus on the finer soil fractions (<10 μm). For each sample, the dust generator was run for 11 min, and it was observed that it took about a minute for the readings to reach a steady state. Particle counts per volume were then converted to concentrations (mg m^{-3}) [see *Bhattachan et al.*, 2012]. The dust concentrations for the size classes between 0.3 and 10 μm were integrated to determine the PM_{10} values (concentration of particulate matter less than 10 μm) and divided by the mass of the sample in order to present the dust concentrations as PM_{10} per unit mass of the sediment sample (Figure 2).

2.3. Soluble Iron

Soil from the Taylor Valley sites, i.e., Lake Bonney Lake Fryxell, and sediment on the surface of multiyear sea ice at the mouth of the Taylor Valley were analyzed for soluble ferrous ion, Fe(II) because Fe(II) is considered the most bioavailable form of iron. For each sample, 0.25 g of sediment was soaked in 10 mL of 0.5 M HCl, shaken for an hour, and then filtered to eliminate particulate matter. The pH of the aliquot was increased to 5.5 with an acetate buffer. Then, 0.1 M ferrozine was added to the solution to measure Fe(II) content spectrophotometrically using a Shimadzu® 4100 UV photospectrometer at 562 nm [*Stookey*, 1970; *Zhu et al.*, 1997]. A standard stock solution (1000 mg/L) of ammonium iron (II) sulfate was prepared in 0.5 M HCl and was diluted with varying concentrations (0, 0.5, 1, 3, 5, 10, 20, and 50 mg/L) to create the calibration curve.

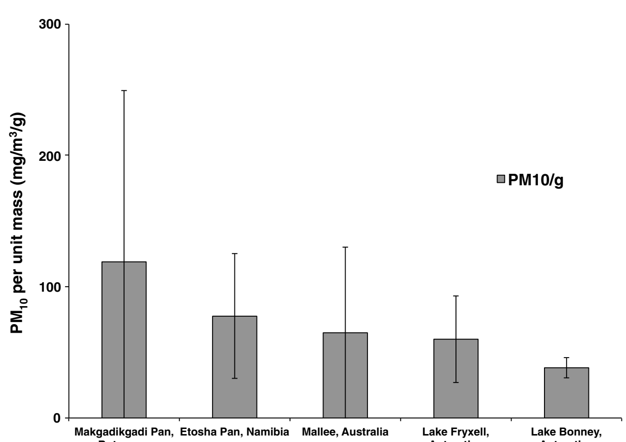

Figure 2. The average PM_{10} concentration per unit mass (mg m^{-3} g^{-1}) of the sediments from the Taylor Valley in McMurdo Dry Valleys with ±1 standard deviation. The average PM_{10} concentration per unit mass of Lake Fryxell and Lake Bonney soils were 60.03 mg m^{-3} g^{-1} and 38.26 mg m^{-3} g^{-1}, respectively. The PM_{10} concentration per unit mass of sediments from the Makgadikgadi Pan, Etosha Pan, and Mallee are calculated following the same parameters in the dust generator [*Bhattachan and D'Odorico*, 2014].

2.4. Forward Trajectory Analysis

To test the aeolian deposition patterns of dust emitted from the study region, we used a trajectory model (HYSPLIT, Hybrid Single-Particle Lagrangian Integrated Trajectory [*Draxler and Rolph*, 2003]) to calculate the terminal points of 7 day forward trajectories of air parcels originating from the Taylor Valley. The model calculates the trajectories using the Global Data Assimilation System 1 data set between the years 2010 and 2013. The model was set up to run forward trajectories starting daily at 5 UTC with a starting altitude of 500 m above sea level.

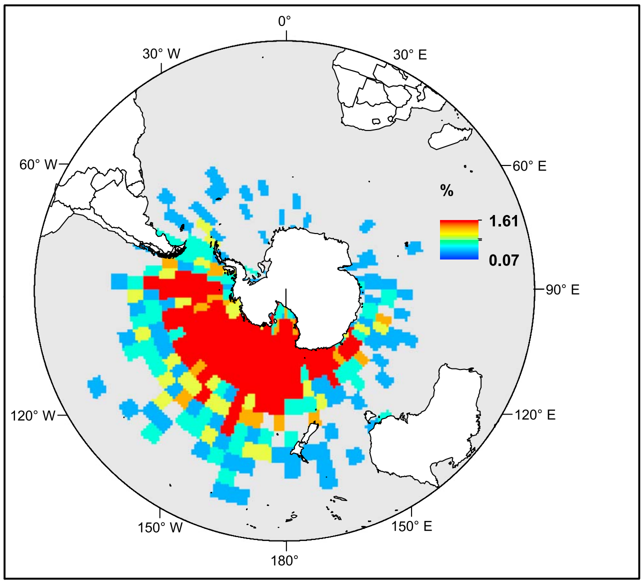

Figure 3. The deposition footprint of the 7 day forward trajectory from a site in Taylor Valley, McMurdo Dry Valleys.

3. Results

The average clay and silt percent for soil samples from the MDVs of Antarctica is 1.04 ± 0.07, 2.28 ± 0.70 for Lake Bonney and 1.60 ± 0.48, 3.57 ± 1.13 for Lake Fryxell (Table 1). We use PM_{10} measurements (per unit sample mass) from the dust generator as indicators of the dust emission potential of each sediment sample. To evaluate the relative importance of the dust generation potential of sources from the MDVs of Antarctica and other active dust sources in the Southern Hemisphere, we compare the PM_{10} values obtained for samples from the MDVs with those from Australia, Namibia, and Botswana [*Bhattachan and D'Odorico*, 2014] (Figure 2). The PM_{10} concentration per unit mass (mg m^{-3} g^{-1}) of sediments from the MDVs is comparable to the potential for dust emission from the agricultural fields in the Mallee region of Australia and slightly lower than those determined for the Makgadikgadi and Etosha saltpans in Southern Africa (Figure 2). The forward trajectory analysis with the HYSPLIT model shows the deposition footprint, expressed as the probabilities that dust from the MDVs is deposited in each of the cells of the 5° by 5° grid used by HYSPLIT (Figure 3). The deposition is largely in the Ross Sea and the Pacific section of the Southern Ocean.

Soil sampled from other Southern Hemisphere dust sources have Fe(II) content of 0.51 ± 0.18 mg/g in the Mallee (Australia), 0.17 ± 0.21 mg/g in the Makgadikgadi Pan (Botswana), and 0.13 ± 0.06 mg/g in the Etosha Pan (Namibia) [*Bhattachan and D'Odorico*, 2014]. Sediments from the Lake Fryxell and Lake Bonney areas of the McMurdo Dry Valleys of Antarctica exhibited a much higher bioavailable iron (Fe(II)) content of 1.51 ± 0.18 and 1.36 ± 0.07 mg/g compared to these currently active dust sources in the Southern Hemisphere (Table 1). Similarly, the soluble iron (Fe(II)) content of sea ice sediments and subsea ice sediments was found to be about 1.55 mg/g, consistently across all sites (Table 1).

4. Discussion

These results show that the potential for dust emissions from sediments collected in the Taylor Valley within the MDVs is of the same order of magnitude as that of sediments from the Mallee region of Australia and slightly smaller than those of currently active dust sources in Southern Africa (Figure 2). We stress that the dust concentrations measured within the settling chamber of the dust generator are not an actual measurement of the dust concentrations as these measurements do not account for the intensity of the wind forcing nor the state of the surface (e.g., percent cover of nonerodible elements). Rather, the dust generator provides a standardized measurement of the ability of soils to generate dust [e.g., *Gill et al.*, 2006]. By comparing values obtained on different sediment samples from different regions of the world it is possible to rank them on the basis of the amount of dust they can generate. This device has been used on soil samples from various dust sources around the world [e.g., *Singer et al.*, 2003; *Bhattachan et al.*, 2012; *Bhattachan and D'Odorico*, 2014].

Lancaster [2002] reported that the aeolian sediment flux in the MDVs is lower than those from warm deserts. The relatively low dust emission rates in Antarctica are overall not surprising if we consider that the mean annual wind speeds are moderate (about 5 m s^{-1}) [e.g., *Doran et al.*, 2002], and the saltation events in this area occur at low temperatures in the range of −40°C to +5°C [*Gillies et al.*, 2013]. Other studies have shown that in the Taylor Valley, maximum wind speeds of 30 m s^{-1} are reported [e.g., *Doran et al.*, 2002]; however, *Gillies et al.* [2013] found that maximum wind speeds did not exceed 25 m s^{-1}. Although soils in Antarctica are generally cemented by ice and sometimes covered by a crust [*Doran et al.*, 2002], a warming of +0.5°C h^{-1} in spring and summer was observed as a precursor to initiate saltation [*Gillies et al.*, 2013]. However, during the winter months, wind gusts can often exceed 37 m s^{-1} [e.g., *Nylen et al.*, 2004], and the occurrence of a dry and ice-free top part of the soil profile associated with hyperaridity may favor saltation and aeolian transport [*Gillies et al.*, 2013]. Several studies predict a possible poleward shift and strengthening of the Southern Hemisphere westerlies that encircle Antarctica [e.g., *Kushner et al.*, 2001; *Yin*, 2005]; however, the simulated surface winds over Antarctica show only small changes over the 21st century [e.g., *Bintanja et al.*, 2014]. We show that soil samples from the Lake Fryxell and Lake Bonney areas in the MDVs showed values of dust yield potential similar to those of other (warmer) dust sources in the Southern Hemisphere (Figure 2). Even though in the global context the actual dust emissions from soils in the MDVs are smaller than those from other dust sources in the Southern Hemisphere, the deposition of dust from Antarctica is likely to have a greater impact on the biogeochemistry of the Southern Ocean [*Jickells et al.*, 2005] both because of the proximity of these dust sources and their relatively high soluble iron content (Table 1).

For dust emissions from the study region to contribute to the fertilization and increase in productivity of the Southern Ocean, this dust will have to be transported by winds to HNLC zones of the ocean. Our forward trajectory analysis shows that the likely deposition footprint of the dust from the MDVs is the Ross Sea and the Pacific Ocean sector of the Southern Ocean (Figure 3). Although this analysis does not actually estimate the amount of dust and/or soluble iron that will be deposited and made available for ocean fertilization, it gives an indication of the region potentially affected by emissions from the MDVs and their likely transport pathway.

Cassar et al. [2007] outlined five mechanisms for soluble iron to reach waters of the Southern Ocean; however, the determination of the transport pathways of iron carried by dust from the MDVs to the Southern Ocean needs further investigation. Based on our trajectory analysis and the current knowledge of ocean current patterns, we propose two main mechanisms for transport of soluble iron from the MDVs to the ocean:

4.1. Direct Aeolian Transport From the MDVs to the Southern Ocean

We hypothesize that dust from the MDVs will be carried to the Southern Ocean during intense wind events. The production of fine particles via aeolian abrasion during saltation is also likely and diminishes over time as the fines are blown away and a deflated surface made of nonerodible clasts starts to armor the underlying fines. The particle size analysis shows that the sediments in the MDVs are richer in silt than in clay (Table 1). This is consistent with grain size of till in the lower Taylor Valley which consists of ~ 7% silt and clay, primarily silt size with typically only 0.1% clay size [*Miller et al.*, 2015]. Sediment blown from the Taylor Valley onto the sea ice up to 8 to 9 km from shore has an even smaller fraction of silt and clay ($<$2% silt and clay, nearly all silt size) [*Miller et al.*, 2015]. The paucity of silt and clay size sediment suggests that the fine components (clay and silt) were either transported farther out to sea or the fine particles can be held down by armoring at their source in the Taylor Valley [e.g., *Campbell et al.*, 1998]. However, there is no definite support for either mechanism in the literature. Hence, if the direct transport to the Southern Ocean mechanism is the dominant one, our hypothesis of stronger dust emissions from the MDVs during intense wind events will be supported.

4.2. Aeolian Transport and Deposition of MDV Sediments Onto Sea Ice

We hypothesize that aeolian transport from the MDVs and deposition onto sea ice that eventually melts is the second mechanism by which soluble iron is transported to the ocean. It is important to note that the source of iron in sea ice is atmospheric dust [e.g., *Martin*, 1990], from both local and distant sources, or sediments sourced from aeolian sediments in the MDVs that are deposited to the sea ice. In our study, we have estimated the soluble iron content of sediments collected from the underlying seafloor and from the surface of the multiyear sea ice; we have shown that these sediments are indeed rich in soluble iron (Table 1). In a recent study, *Chewings et al.* [2014] found that the McMurdo Ice Shelf debris bands (south of the MDVs) are the largest source of sediment entrained in annual snow on the sea ice within McMurdo Sound with potential contributions to sea floor sedimentation [e.g., *Atkins and Dunbar*, 2009] and supply of soluble iron to the Ross Sea [e.g., *Edwards and Sedwick*, 2001; *Arrigo and van Dijken*, 2004]. Although the extent of increased productivity of the Southern Ocean by exposure of the sediment in the debris bands is not explored in this study, we show that the sediment collected from the multiyear sea ice sourced from the moraines in the Taylor Valley is rich in soluble iron and the melting of sea ice is expected to contribute iron to the Southern Ocean. We argue that the sea ice sediment may be carried farther away from the continent, as little is known about where the sea ice travels before melting. We notice that previous studies have evaluated the contribution of bioavailable iron from melting of sea ice in the Ross Sea [e.g., *Sedwick and DiTullio*, 1997] and established the close link between sea ice retreat and increased productivity [e.g., *Arrigo and van Dijken*, 2004].

5. Conclusions

Our results show that the dust-generating potential of the MDVs soil is comparable to that of other dust sources in the Southern Hemisphere and the emitted dust is likely deposited in the Ross Sea and the Southern Ocean. Furthermore, we analyzed the sediments under the sea ice for soluble iron and found that the sediment on the surface and under the multiyear sea ice is rich in soluble iron. These sediments could also contribute to ocean productivity, though the relative importance of this source of bioavailable iron (compared to aeolian dust) is not explored in this study. Finally, it is unclear at what rate changes in regional climate could enhance the aeolian activity in the MDVs and turn them into a potentially important dust source. The rate of warming in the second half of the twentieth century has been high in Antarctica [e.g., *Vaughan et al.,* 2003]. Previous research suggests that an intensification of Southern Hemisphere winds [e.g., *Yin*, 2005], and a positive Southern Annular Mode trend would increase the frequency of windy days in the summer and also the days with average temperature greater than 0°C which could lead to greater melting and thawing in the MDVs [e.g., *Speirs et al.*, 2013]. Thus, we expect that increased wind speed and temperature might enhance dust emissions and the increased flux of iron-rich dust to the Southern Ocean could impact its productivity.

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